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INFRARED SENSING OF BUOYANT SURFACE PLUMES

by

Ole Petersen [1] and Torben Larsen[2]
Department of Civil Engineering
University of Aalborg,
Sohngårdsholmsvej 57, DK-9000 Aalborg, Denmark

Summary
This paper is concerned with laboratory experiments on buoyant surface plumes where heat is the source of buoyancy. Temperature distributions were measured at the water surface using infrared sensing, and inside the waterbody a computer based measurement system was applied. The plume is described by numerically integrated length scales. Comparisons between depth integrated scales and scales based on surface temperatures are made.

1. Introduction

The capability of computers to control complicated operations and handle large amounts of data has removed the necessity of many restrictive assumptions imposed on hydraulic theories, merely to reduce the amount of data from experiments.

In the experiments to be presented herein integral scales of buoyant surface plumes are obtained from a combination of an automatic temperature measurement system and numerical integration, thus avoiding the profile assumptions usually inherited in integral descriptions [4].

The experiments are concerned with the dilution of sewage in the near field of sea outfalls, and represents a portion of a project which seeks to establish a description of the dilution processes.

The purpose of this study has been to gain some experience in applications of infrared sensing with respect to laboratory experiments and to investigate if there exists a relation between integral properties of buoyant surface plumes and characteristics obtained from temperature measurements at the water surface.

2. Dispersion of buoyant surface plumes

The following text gives a brief summary of some of the basic assumptions made with respect to dilution of buoyant surface plumes.

The buoyant surface plume represents a link between the pure gravitational spread of a light fluid over a denser fluid and the turbulent diffusion of a passive contaminant.

[1]M.Sc. Civ.Eng., Ph. D. student
[2]M.Sc. Civ. Eng., Assoc. Prof.

In an ideal situation where sewage is relased into a saline recipient with uniform density and velocity the rising sewage will reach the water surface. A relatively wide and thin plume forms due to the residual density difference between the diluted sewage and the ambient water. The plume will be convected downstream by the ambient flow, while further dilution takes place mainly in vertical direction due to turbulent diffusion, though attenuated by the presence of vertical density gradients.

The size of the largest turbulent eddies will eventually exceed the plume width, and dispersion due to translation of the plume will occur.

The experimental model of this situation is shown in Figure 1.

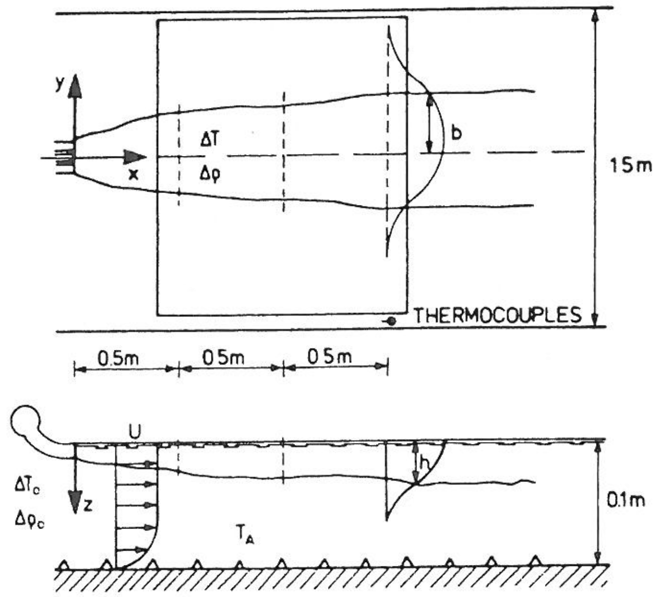


Figure 1: The situation under study.

Heated water is released at the surface of a channel flow through three circular nozzles parallel to the direction of the main flow. There is no excess momentum in the jets, thus no significant shear between the jets and the ambient water is present.

The plume is described by two integral scales, a plume width, b, and a plume height, h. These are determined by the buoyancy , characterized by a mean density difference, $\overline{\Delta\rho}/\rho$, the flow velocity, U, and the level of ambient turbulence characterized by shear velocity, U_f, and the water depth, d . The problem can be formulated as

$$\frac{db}{dx} = f\left(\frac{\overline{\Delta\rho}}{\rho}\ ,\ U\ ,\ U_f\ ,\ d\right) \tag{1}$$

$$\frac{dh}{dx} = g\left(\frac{\overline{\Delta\rho}}{\rho}\ ,\ U\ ,\ U_f\ ,\ d\right) \tag{2}$$

where any dependence on empirical constants has been omitted.

3. Integral scales

The integral scales b and h are to be determined from measured cross sectional distributions of density differences.

A time average mass deficit per downstream distance is defined as

$$M = \int_{-\infty}^{\infty} \int_{0}^{d} < \Delta\rho(t\ ,\ y\ ,\ z) > dz\, dy \tag{3}$$

Here $<\ >$ denotes ensemble average, or considering the plume as the superpositions of elementary puffs, a time average. $\Delta\rho$ is density difference to time t.

The plume width is defined as

$$b^2 = \frac{1}{M} \cdot \int_{-\infty}^{\infty} \int_{0}^{d} < \Delta\rho(t\ ,\ y\ ,\ z) > (y- < \bar{y} >^2) dz\, dy \tag{4}$$

and similar for the height

$$h^2 = \frac{1}{M} \cdot \int_{-\infty}^{\infty} \int_{0}^{d} < \Delta\rho(t\ ,\ y\ ,\ z) > z^2\, dz\, dy \tag{5}$$

where $< \bar{y} >$ is the lateral coordinate of the center of mass.

Based on these fundamental scales a mean density difference will be defined as

$$< \overline{\Delta\rho} > = M/2 \cdot h \cdot 4 \cdot b \tag{6}$$

When only temperatures at the water surface are available, a characteristic plume width is defined as

$$b_S^2 = \frac{1}{< M_S >} \int_{-\infty}^{\infty} < \Delta T(t\ ,\ y) > (dy- < \bar{y} >)^2\, dy \tag{7}$$

where M_S is now the area contained under the lateral temperature profile and $\Delta T(t\ ,\ y)$ is temperature to time t in distance y from the axis.

Due to the order of integrations in the definitions above it is implied that the actual plume width comfortably exceeds the size of the largest turbulent eddies. Otherwise the length scale b will tend to be wider than the actual plume width.

In the laboratory this is usually not a serious problem but, due to the existence of large scale turbulence, it represents a serious complication to field studies.

An average plume width that neglects these effects has been suggested by Batchelor, [3] as an ensemble average plume width, b_L

$$b_L^2 = \left\langle \frac{1}{M_L} \int_{-\infty}^{\infty} \Delta T(y)\,(y - \bar{y})^2\, dy \right\rangle \tag{8}$$

here based on surface temperatures.

In the experiments here these integrals are evaluated numerically, thus no assumptions of profile shapes have been made.

4. Experiments

The experiments were conducted in a recirculating hydraulic flume, 1.5 m wide , 25 m long and with water depth at 0.1 m. Two bed types were used with a sand grain roughness at 0.7 mm and 40 mm. Heated water was supplied from a 180 l insulated constant head barrel. A sketch of the measurement set up is shown in Fig. 2.

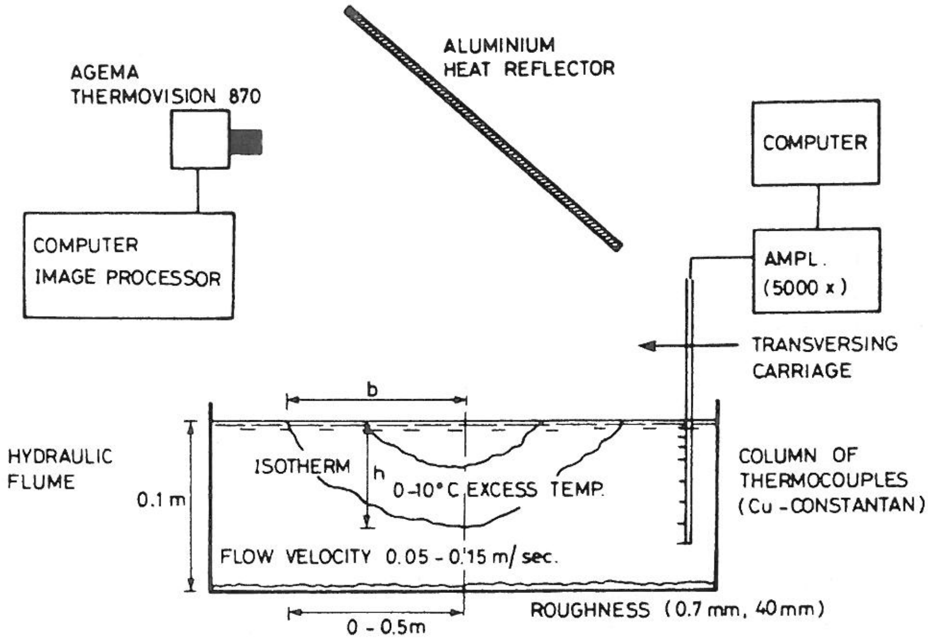


Figure 2: Measurement set up.

Temperatures below the water surface were measured using a column of 8 Cu-Constantan thermocouples mounted on a transversing carriage. Sampling and transversing were controlled by a computer. From each thermocouple a time average density difference was calculated according to

$$< \Delta\rho(z) > = \frac{1}{N} \sum_{i=1}^{N} f\left(T_i(z)\right) - f\left(T_A\right) \tag{9}$$

where f is a functional dependency between density and temperature, obtained from quadratic interpolation in a density- temperature table for fresh water, T_A is ambient temperature and T_i actual temperature in depth z.

Surface temperatures were measured using an infrared sensitive video camera (type AGEMA Thermovision 870). Mounted with a HgTeCd-detector this camera is sensitive to thermal radiation at wavelengths from 2.5 to 5 μm. In this near-infrared bandwidth , water emits radiation nearly as an ideal black body. The measured temperature is thus mostly dependent on radiation from the upper $10 - 20\ \mu m$ of the water [4]. All measurements were adjusted according to an estimated emmisivity of 0.92.

The camera scanned an area of $1.3 \cdot 1.3\ m^2$ 25 times per second in the present set up. The spatial resolution was $1.5 \cdot 1.5\ cm^2$ when measured at the water surface. Sensitivity of the camera was $0.1\ °C$, and absolute temperatures could be measured to within approximately $2\ °C$.

All recordings were stored on videotape for later processing in an image processing microcomputer, from which various 140 x 140 pixel sized, coloured thermal images could be obtained.

Due to a limited height of the room a high-polished aluminium heat reflector was installed. Great care was taken to avoid any distortions due to curvature of the reflector.

Three rods with knots for every 0.1 m mounted near the water surface constituted a length scale reference.

The experiments were conducted for a range of density differences, levels of turbulence and velocities. The conditions are shown in Table 1.

Table 1. Experimental conditions.

No.	U cm/s	k mm	T_A °C	ΔT_o °C
1.1	10.2	0.7	21.2	25.6
1.2	10.2	0.7	21.3	10.9
1.3	10.2	0.7	21.3	3.5
1.4	10.2	40	21.6	3.7
1.5	10.2	40	21.8	10.1
1.6	10.2	40	22.1	14.9
2.1	5.7	40	22.2	14.3
2.2	15.1	40	22.2	14.3

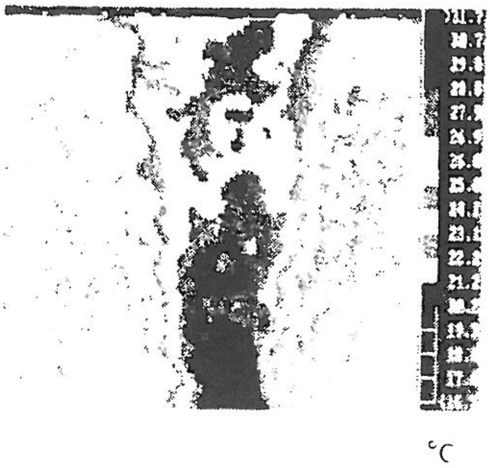
k is equivalent sand grain roughness,
T_A temperature of ambient water, and
ΔT_o initial excess temperature.

5. Results

The results from the infra-red recordings are thermal images showing the temperature at the water surface as shown in Fig. 4.

From series of thermal images mean temperatures were calculated by image accumulation as shown in Fig. 5. All temperature fluctuations are removed by the averaging, and mean temperatures appear to be steady. The distribution of mean temperatures in three downstream cross sections are also shown. From paper hardcopies these were digitized and the plume widths, b_S, were calculated.

The distribution of density differences was measured in the cross-section 1.5 m downstream, and the depth integrated plume width, b, was obtained by numerical integration of the measured profile.



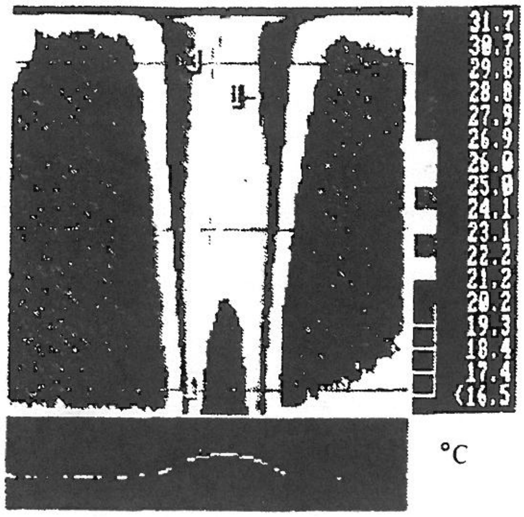


Fig. 4: Instantaneous temperatures. Run no. 1.6.

Fig. 5. Time average temperatures. Accumulated from 20 images of a 60 sec. recording.

Both plume widths are shown in Table 2. The ratio of the surface plume width, b_S, to the width of the density profile seems to increase from the value of 1.0 with decreasing buoyancy. Inspections of cross sectional isodensity patterns suggested that this increase is due to a quicker deepening in the central parts of the plume, thus bell shaping it. A similar observation was made by Weill and Fischer [2]. No conclusive explanation of this phenomenon seems evident. From a study of very high and narrow plumes Prych [5] has suggested the existence of secondary currents.

In run no. 1.1 and 1.6 the average plume width, b_L, was calculated from series of instantaneous surface temperature profiles. Comparison with the width of mean temperature profiles showed no significant deviation, thus indicating that the plume is wider than the length scale of the turbulent velocity fluctuations.

6. Concluding remarks

Seen from an experimental point of view has the application of numerically integrated length scales some advantages. The scales characterizing the plume do not rely on the accuracy of the value estimated in i single point, but on the sum of all measurements in a cross section. Random deviations are averaged in a statistically consistent manner.

Table 2: Summarized results of the experiments

	b_L cm Distance from outlet			b	b_S/b
Run no.	0.5 m	1.0 m	1.5 m	1.5 m	1.5 m
1.1		14.3	20.0	19.7	1.01
a)		14.1	20.2		
1.2	6.8	9.9	14.1	13.1	1.07
1.3	6.2	7.4	10.2	8.3	1.22
1.4	5.4	7.1	9.6	7.1	1.35
1.5	7.0	9.5	13.2	12.2	1.08
1.6	7.8	11.5	15.3	13.6	1.12
b)	7.8	10.9	15.2		
2.1	12.6	18.2	24.5	24.1	1.02
2.2	6.0	7.4	10.6	9.1	1.17

note: a) and b): average plume width b_L.

The infrared sensing system used here, did provide some new features with respect to flow-visualization and evaluation of Langrangian types of characteristics. It seems though, that it should be refined with faster and more advanced image processing techniques allowing for automatic evaluation of length scales and statistics of temperature fluctuations.

7. References

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